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The population of massive X-ray binaries*

I. The Large Magellanic Cloud

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Abstract. We present high resolution blue spectroscopy of an almost complete sample of optical counterparts to massive X-ray binaries in the Large Magellanic Cloud (LMC) and derive their spectral classification. We find an spectral type B0II for the optical counterpart to RX J0532.5−6551, confirming it as the first wind-fed massive X-ray binary in the LMC. We also confirm the Be nature of the proposed counterpart to RX J0535.0−6700. The proposed optical counterpart to RX J0531.5−6518 is a B2V star with signs of emission in the Balmer lines. In total, we give accurate spectral types for 14 counterparts. We find that the overall observed population of massive X-ray binaries in the LMC has a distribution not very different from the observed Galactic population and we discuss different selection effects affecting our knowledge of this population. The spectral distribution of the Be/X-ray binary population is also rather similar to the Galactic one. This distribution implies that Be/X-ray binaries must have preferentially formed from moderately massive binaries undergoing semi-conservative evolution. The observation of several Be/X-ray binaries with large eccentricities implies then the existence of supernova kicks.

Key words. binaries: close – x-rays: binaries – stars: early-type – stars:emission line, Be – galaxies: Magellanic Clouds

1. Introduction

High Mass X-ray Binaries (HMXBs) are X-ray sources composed of an early-type massive star and an accreting compact object (generally a neutron star, but occasionally a black hole). HMXBs are traditionally divided (see Corbet 1986) into Classical or Supergiant X-ray binaries (SXBs) in which the compact object accretes from a mass-losing OB supergiant or bright giant and Be/X-ray binaries (BeXBs), in which a neutron star orbits an unevolved OB star surrounded by a dense equatorial disc (cf. Liu et al. 2000 for a recent catalogue), though the physical reality could be rather more complex (cf. Negueruela & Reig 2001). Different population synthesis analyses predict that the vast majority of HMXBs will be BeXBs, though this is not apparent from the number of sources detected in the Milky Way (where $\sim 30\%$ of known systems are SXBs), presumably due to different selection effects that will be detailed later on.

Apart from their intrinsic interest as high-energy radiation sources, HMXBs offer a window on the late stages of massive binary evolution. Their properties as a population can be used to extract valuable information on the different stages of the life of massive binaries.

In order to understand the representativity of the known sample of Galactic HMXBs, it is of fundamental importance to have at least an approximate idea of the HMXB population content in other Galaxies. The Magellanic Clouds (MCs) present a unique opportunity to carry out such a study, since they have a structure and chemical composition which differs from that of the Milky Way and, at the same time, are close enough to allow the study of individual sources with modest-sized ground-based telescopes.

For this reason, we have undertaken an observational campaign in order to obtain high Signal-to-Noise Ratio (SNR) spectroscopy of the optical counterparts to MC HMXBs which will allow us to derive accurate spectral classifications for these stars. Such work is imperative if we are to gain some understanding of the mass distribution and evolutionary status of the HMXB populations.

In this first paper, we centre on the HMXB population of the LMC. This population is relatively small and all the optical counterparts are reasonably bright, allowing us to obtain a basically complete sample. In further works, we will study the SMC population and will compare the

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characteristics of the MC populations with the Galactic one.

2. Sample and Observations

Spectra in the classification region were obtained using the ESO 1.52-m telescope at La Silla Observatory, Chile, equipped with the Boller & Chivens spectrograph. On the nights of 30th and 31st October 1999, the spectrograph was fitted with the #32 holographic grating and the Loral #38 camera, which gives a nominal resolution of ~ 0.5Å/pixel. On 1st November 1999 and 15th September & 22nd October 2000, we used the #33 holographic grating instead, which gives a resolution of $\sim$ 1.0 Å/pixel. Measurements of arc line FWHMs indicate spectral resolutions of ≈ 1.4Å and ≈ 3.0Å at ~ 4500Å, respectively.

The configurations selected introduce a magnitude limit (the magnitude at which a 40-min integration with the #33 grating would not give an adequate SNR for accurate spectral classification) at $B \lesssim 16$. The only HMXB in the LMC whose optical counterpart is fainter than this limit is LMC X-3. We obtained a lower resolution spectrum of this source on 10th February 2001 with the Danish 1.54-m telescope at La Silla Observatory, Chile, equipped with the Danish Faint Object Spectrograph and Camera (DFOSC) and grism #3.

All the data have been reduced with the *Starlink* packages CCDPACK (Draper et al. 2000) and FIGARO (Shortridge et al. 1999) and analyzed using FIGARO and DIPSO (Howarth et al. 1998). Photometry for some of the objects has been obtained as part of the Southampton/SAAO HMXB campaign. It has been taken during several runs using the SAAO 1.0-m telescope. The photometric data are listed in Table 1.

Our sample is complete, in the sense that we present accurate spectral classifications for the 14 LMC MXBs with secure optical identifications listed in the catalogue of Liu et al. (2000). Recent deep surveys of *ROSAT* sources in LMC fields have failed to detect many new HMXB candidates, in spite of intensive work (Haberl & Pietsch 1999a; Sasaki et al. 2000). Three other massive stars have been suggested as counterparts to possible MXBs, but they have not been included in the sample. Among this, the identification of RX J0516.0−6916 with a $V = 15.0$ B1V star was suggested by Cowley et al. (1997), but considered uncertain because the star did not display any characteristics of Be behaviour at the time of the observations. Sasaki et al. (2000) suggest the identification of RX J0541.4−6936 with the LMC supergiant Sk −69° 271 (whose magnitude is listed as $B = 11.6$, and not $B = 18.8$ as given by Sasaki et al.) because of positional coincidence. Finally, RX J0532.4−6535 was suggested by Haberl & Pietsch (1999) as a Be/X-ray binary, because of its coincidence with a variable star in the catalogue of Reid et al. (1988), namely GRV 0532−6536. Two other *ROSAT* PSPC sources which show positional coincidence with stars in this catalogue turn out to be Be/X-ray binaries (see later the discussion on RX J0535.0−6700), even though objects in this catalogue were originally believed to be Mira variables. However, the coulour given by Reid et al. (1988) for GRV 0532−6536 $(V - I) = 2.02$ strongly suggests that it is indeed a red star and not an LMC Be star.

3. Spectral classification

Due to the smaller metal content of the LMC with respect to the Milky Way, spectral classification of LMC sources cannot be achieved with a straightforward comparison to Galactic MK standards. Though some effort has been done in establishing a classification scheme for the brightest LMC supergiants (e.g., Fitzpatrick 1991), this work has not been extended to lower luminosities.

The metallic lines in LMC supergiants are on average 30% weaker than in Galactic objects of the same spectral type and luminosity class, but there is some dispersion (Fitzpatrick 1991). Such a decrease in intensity may mean that what appears as a weak line in the spectrum of a bright Galactic MK standard is lost in the noise in the spectrum of an LMC source. This complicates specifically the luminosity classification. Since the spectral classification (and specially the luminosity classification) of Be stars is already difficult for Galactic objects due to the presence of emission components (see Steele et al. 1999 for a general discussion), great care has to be taken when obtaining spectral types for the counterparts to MXBs in the LMC.

For this reason we have adopted the criterion of assuming that all Be stars are main-sequence objects unless the intrinsic magnitudes derived from photometry of the objects suggest a higher luminosity class. In what follows, we will adopt the value of the distance modulus derived by Udalski (2000) from the results of the OGLE-II microlensing experiment, i.e., $(M - m)_0 = 18.24$. Since this value is considerably smaller than values adopted before, the effect of this choice will be discussed in Section 4.

One main source of difficulty stems from the fact that the circumstellar disk around a Be star can contribute to its luminosity. In principle, since the disks have relatively low temperatures compared to the central stars (typically $T_{\rm disk} \approx \frac{1}{2}T_{\rm eff}$), the disk contributes significantly to the continuum emission (and hence the total luminosity) only at relatively long wavelengths (near- and mid-IR), giving rise to what is generally known as *infrared excess* (e.g., Slettebak 1988). However, variability by up to ~ 0.5 mag in the V and R bands is not infrequent in isolated (i.e., without a binary companion) Be stars and variability in the B band can be substantial, even if it is not expected from modelling (Dachs et al. 1988).

3.1. RX J0532.5−6551 = Sk −65° 66

RX J0532.5−6551 is a very variable (up to a factor of 66; Sasaki et al. 2000), apparently persistent, not very bright ($L_{\rm x} \sim 1 \times 10^{35}\ {\rm erg\,s^{-1}}$) X-ray source, associated with the bright star Sk −65° 66 (Haberl et al. 1995a). All these

Table 1. Photometric observations of the sources discussed. For EXO 053109−6609 see text.

Object	Date	B	V	R	Error
RX J0532.5−6551	4 Oct 1996	13.00	13.09	13.17	0.01
LMC X-4	6 Oct 1996	14.38	14.44	14.86	0.03
LMC X-3	20 Jan 2001	16.85	16.74	16.89	0.05
CAL E	3 Oct 1996	14.35	14.42	14.44	0.01
CAL 9	2 Oct 1996	14.48	14.36	14.23	0.02
RX J0520.5−6932	4 Oct 1996	14.42	14.40	14.32	0.03
RX J0544.1−7100	24 Jan 1999	15.35	15.25	15.18	0.01
RX J0529.8−6556	25 Jan 1999	14.65	14.81	14.96	0.01
RX J0531.5−6518	21 Jan 1999	15.86	16.02	16.11	0.02
H0544−665	1 Oct 1996	15.20	15.55	15.26	0.01
1A 0535−66	20 Jan 2001	14.91	14.90	15.30	0.04
RX J0535.0−6700	19 Jan 1999	14.80	14.87	14.91	0.01

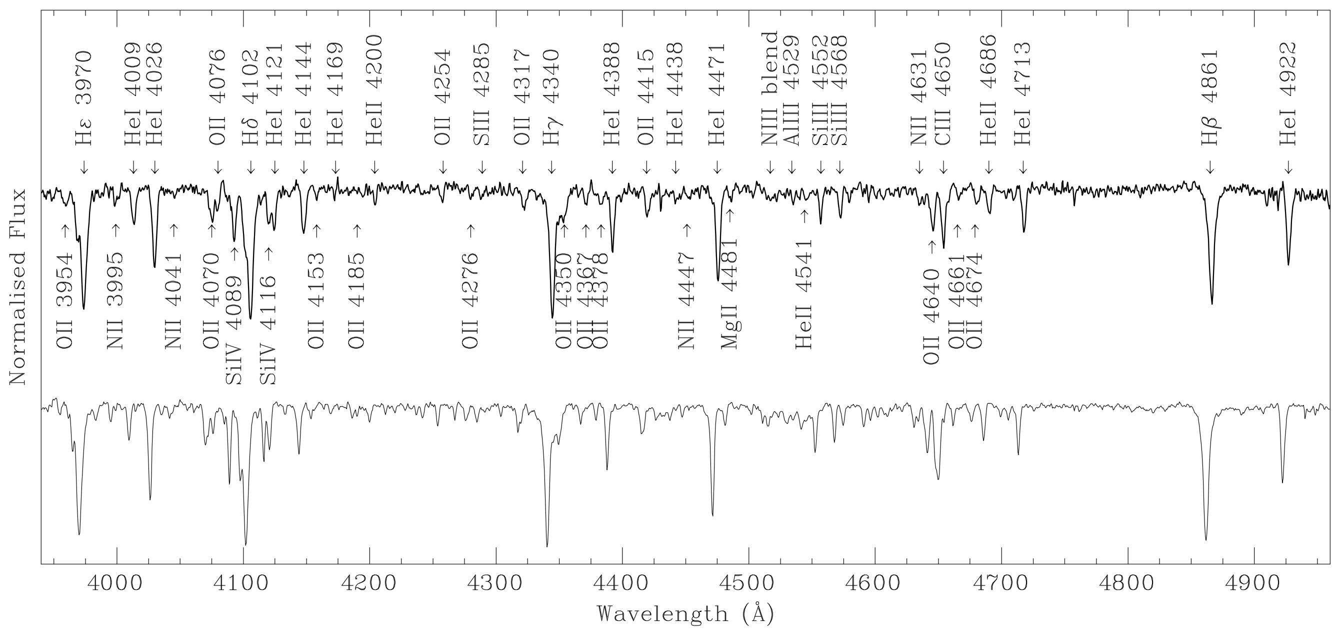

Fig. 1. Blue spectrum of Sk −65° 66 (top), compared to that of the B0III MK standard HD 48434 observed with the same instrumentation. Features detected on the spectrum of HD 48434 have been marked on the spectrum of Sk −65° 66 in order to facilitate comparison. Note the weaker He II λ4686Å in the spectrum of Sk −65° 66 and the general shift in wavelength of all the lines due to the LMC systemic radial velocity.

characteristics make it the only LMC X-ray source proposed to be an analogue to the Galactic wind-fed SXBs. In Fig. 1, we present the classification spectrum of Sk −65° 66, together with that of the B0III MK standard HD 48434.

The spectrum of Sk −65° 66 displays weak He II lines, indicating a spectral type close to B0. The richness of the metallic spectrum would prevent a main-sequence classification even for a Galactic object. In Fig. 1, we can see that the strength of the oxygen spectrum in Sk −65° 66 is comparable to the B0III Galactic standard, while the Si III and Si IV lines are slightly weaker. The strength of the H I and He lines (which are not affected by metallicity) is similar to that of the B0III standard, though always slightly weaker. The He II λ4686Å line, which is the main luminosity indicator, is clearly weaker in Sk −65° 66, suggesting a slightly higher luminosity. Therefore the spectrum indicates a spectral type of B0II for Sk −65° 66.

For this spectral type, Wegner (1995) gives an intrinsic colour $(B-V)_0 = -0.22$. Our photometric data, $V = 13.09$, $(B-V) = -0.09 \pm 0.02$ then imply a reddening $E(B-V) = 0.13$, consistent with the average for LMC sources. Assuming standard extinction $A_V = 3.1E(B-V)$, this results in an intrinsic luminosity $M_V = -5.6$, which is too high for a B0III star (Vacca et al. 1996), but compatible with a B0II or B0Ib spectral type. We conclude then that Sk −65° 66 has a spectral type B0II, confirming it as the first wind-fed SXB in the LMC.

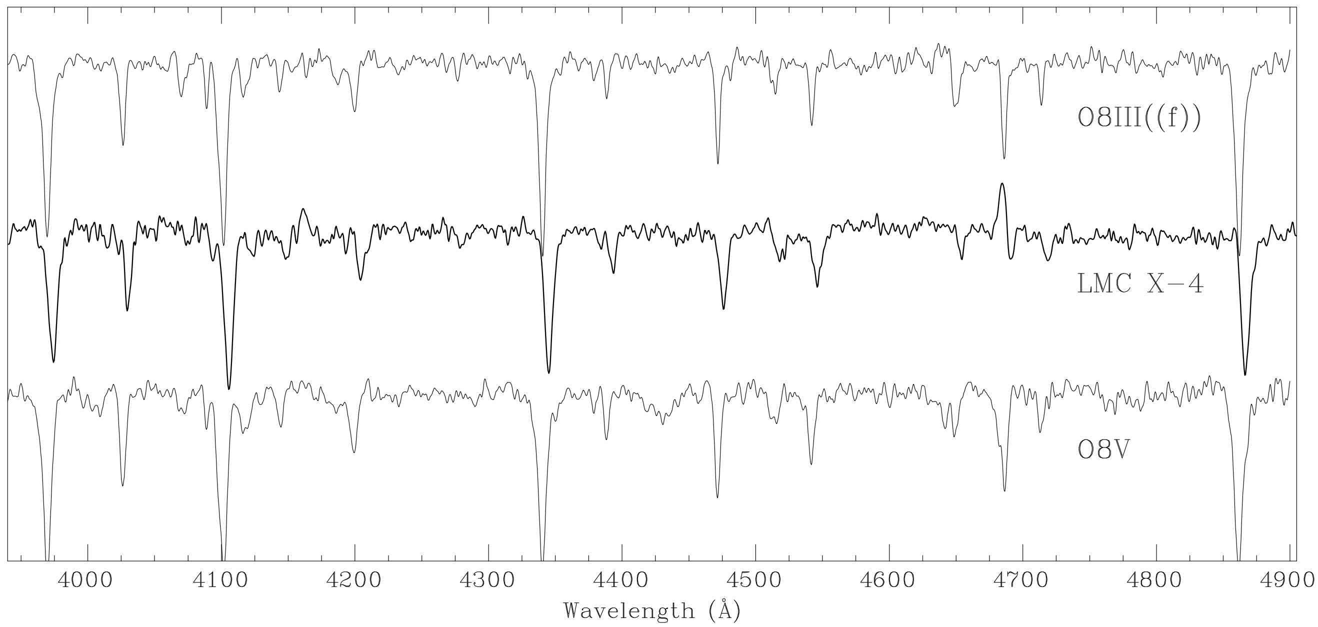

Fig. 2. Blue spectrum of the optical counterpart to LMC X-4, (middle) compared to MK standard stars for spectral types O8III((f)) (HD36861) and O8V (HD48279). The apparent emission feature around ≈ 4160 in the spectrum of LMC X-4 is due to a cosmic ray hit. Note the photospheric component of He II λ4686Å, clearly visible in spite of the strong emission from the vicinity of the compact object. The spectra, as in all the following figures, have been smoothed with a Gaussian filter for display.

3.2. LMC X-4

This very bright (up to $\sim 5 \times 10^{38}\,\mathrm{erg\,s^{-1}}$), variable and persistent X-ray source is a 13.5-s X-ray pulsar (Kelley et al. 1983). The system has been extensively studied and it is understood in terms of a neutron star in a 1.4-d orbit around a massive O-type star close to filling its Roche lobe (Chevalier & Ilovaisky 1977). A strong 30-d modulation in the optical and X-ray lightcurves is identified in terms of a precessing accretion disc (e.g., Heemskerk & van Paradijs 1989).

Chevalier & Ilovaisky (1977; see also Ilovaisky et al. 1984) observed photometric variability with an amplitude of ~ 0.2 mag in the B-band and some changes in the width and strength of lines in the spectrum in phase with the 1.4-d orbital period. The spectral class, however, was approximately constant in spite of the expected X-ray heating of the O-star surface. Their average spectrum was that of an O8III–V star with weak variable He II λ4686Å emission superimposed on the stellar spectrum. The radial velocity of the emission line varied strongly, indicating that it is produced close to the compact object. Further spectroscopic observations by Hutchings et al. (1978) found very weak or absent He II λ4686Å emission, but suggested changes in the spectral type with the orbital period.

Our spectrum of LMC X-4 is displayed in Fig. 2 together with MK standard stars for spectral types O8III((f)) (HD36861) and O8V (HD48279), taken from the digital atlas of Walborn & Fitzpatrick (1990). Even though there is relatively strong He II λ4686Å emission (much stronger than in any of the spectra of Hutchings et al. 1978), the underlying photospheric feature is clearly visible. As indicated by Chevalier & Ilovaisky (1977), the spectrum seems intermediate between O8V and O8III, with the strength of the He lines closer to the giant. The ratio Si IV λ4089Å/He I λ4143Å, which is the main luminosity indicator for Conti & Alschuler (1971) also seems intermediate, but closer to the giant. The fill-in and possibly marginal emission in N III λ4640Å should confirm that the star is relatively evolved, as its position in the HR diagram indicates (cf. Savonije 1980), though this emission could originate close to the compact object.

Therefore a spectral type O8III seems adequate. Ilovaisky et al. (1984) determined the average colour of LMC X-4 to be $(B-V) = -0.23$, consistent with the $E(B-V) = 0.05$ derived from ultraviolet observations. Then $B = 13.96$ (average of the X-ray off states) implies $M_V = -4.2$. We have then to conclude that the source is underluminous for its spectral type – even for O8V, Vacca et al. (1996) give $M_V = -4.7$. One possible explanation may be that the observed spectral type is due to the deformation and heating of a star of considerably lower mass than corresponds to this spectral type by the compact companion.

3.3. LMC X-1

The optical counterpart for this X-ray source was finally identified with an O-type star (star #32) by Cowley et al. (1995), based on *ROSAT* observations. Previous positions did not allow to choose between this star and a nearby

B supergiant. Hutchings et al. (1983) showed that the O star was a spectroscopic binary with a likely 4.2-d period, suggesting a massive companion. This star is surrounded by a bright emission nebula, likely to be partly ionized by the X-ray flux (Pakull & Angebault 1986). The lack of pulsations and the soft X-ray spectrum make LMC X-1 a clear black-hole candidate. The X-ray source is persistent and the luminosity is high ($\approx 2 \times 10^{38}\,\mathrm{erg\,s^{-1}}$).

The spectrum of star #32 is displayed in Fig. 3, together with that of a second O-type star immersed in the nebulosity. The spectrum is dominated by the very bright emission lines from the surrounding nebula and has been scaled so as to display the photospheric features clearly. These are very weak in both stars, but even more so in the spectrum of star #32. The absolute weakness of the He II lines (apart from He II λ4686Å which has a strong nebular component) is unlikely to be due to in-filling by nebular emission (since the sky spectrum does not show these lines in emission – see Fig. 3) and may suggest that there is some contribution of the accretion disk around the compact object to the continuum.

Though the ratio He II λ4541Å$\simeq$ He I λ4471Å implies a spectral type close to O7, the strength of the He I line is probably affected by nebular emission (see the spectrum of the second O-type star where this line is seen in emission). The possible presence of C III λ4187Å and relatively strong Mg II λ4481Å favours a spectral type O8III (see Fig. 2). Assuming that the reddening to the star has a component $E(B-V) = 0.05$ due to Galactic foreground absorption and $E(B-V) = 0.32$ due to the surrounding nebulosity (Bianchi & Pakull 1985), an absolute magnitude $M_V = -4.9$ is derived. This is slightly too bright for a main-sequence O8 star and slightly too faint for a giant, in good agreement with the spectral classification (given the uncertainty in the reddening law that should be used for the nebular component). Our photometric data from 1996 are also compatible with these values.

3.4. LMC X-3

LMC X-3 is a very bright X-ray source ($L_\mathrm{x} \approx 10^{38}\mathrm{erg\,s^{-1}}$). An orbital solution for LMC X-3 was first proposed by Cowley et al. (1983), based on spectroscopy of the optical counterpart, for which they suggested a spectral type B3V. They derived a 1.70-d period and a mass for the compact object $M_\mathrm{x} > 7.0\,M_\odot$ and likely $9\,M_\odot$, clearly indicating that it is a massive black hole. From photometric observations, van der Klis et al. (1985) were able to refine the orbital period to $P = 1.70479$ d and constrain the black hole mass to $9\,M_\odot < M_\mathrm{x} < 13\,M_\odot$. Such values imply $M_\mathrm{x} > M_*$, a situation in which stable mass transfer via Roche-lobe accretion can take place. However, Soria et al. (2001) have argued that the optical star must have a spectral type B5IV in order to fill its Roche lobe.

The optical counterpart to LMC X-3 is very variable, changing between $V = 16.5$ and $V = 17.3$, indicating that optical emission from the vicinity of the compact object (presumably an accretion disk) can actually dominate the total output. Recent *RXTE* observations have shown that LMC X-3, like most black-hole candidates (but not LMC X-1), oscillates between X-ray states, characterized by a softer spectrum when the luminosity is higher (Wilms et al. 2001). Our spectroscopy was taken when the X-ray luminosity was relatively high, according to the *RXTE*/ASM quicklook results.

The spectrum of LMC X-3 is displayed in Fig. 4, together with that of the B2V MK standard 22 Sco. As remarked by previous authors, the intensity of the Balmer lines in the spectrum of LMC X-3 is much smaller than expected, presumably due to the fact that the accretion disk around the black hole contributes a substantial fraction of the continuum (as is expected from the photometric variations). Some He I lines are comparatively very strong, specially He I λ4471 Å and other triplet lines. Their strength is absolutely inconsistent with a B5 classification. Their ratios with respect to the Balmer line suggest a spectral type even slightly earlier than the B3V proposed by Cowley et al. (1983). However, it is clear that the spectrum is not that of a normal star. We observe broad emission corresponding to He II λ4686 Å and perhaps the Bowen blend. This emission, which must originate from the accretion disk, has never been reported before. Even more puzzling are the strong absorption features at $\sim\lambda$4260Å and $\sim\lambda$4520Å, which do not correspond to any lines generally seen at this spectral type.

Therefore it is difficult to assign a spectral type to the optical counterpart to LMC X-3. Based on the strength of the He I lines, the spectral type should be around B2.5V, but we doubt that such a spectral classification is really reflecting the properties of the star. We suspect that the strength of these lines must be reflecting an overabundance of He in the outer layers of the star.

3.5. CAL E

The X-ray source RX J0502.9−6626 was originally detected by the *Einstein* observatory (Cowley et al. 1984) at a flux of $\sim 3 \times 10^{36}\ \mathrm{erg\,s^{-1}}$. The source was detected three times with the *ROSAT* PSPC at luminosities $\sim 10^{35}$–$10^{36}\mathrm{erg\,s^{-1}}$ and once with the HRI during a bright outburst at $\approx 4 \times 10^{37}\ \mathrm{erg\,s^{-1}}$ (Schmidtke et al. 1995). During the outburst, pulsations at $P_\mathrm{s} = 4.0635$ s were detected. The identification of this source with the Be star [W63b]564 = EQ 050246.6−663032.4 (Woolley 1963) was confirmed by Schmidtke et al. (1994).

The spectrum of the optical counterpart to CAL E is displayed in Fig. 5. The obvious presence of He II λ4686Å and absence of He II λ4200Å indicate that the spectral type is close to B0. If the object is on the main sequence, the strength of Si IV λ4089Å indicates a spectral type B0.2 or earlier. Since C III λ4650Å $\gtrsim$ He II λ4686Å and He II λ4200Å is not seen, the object cannot be earlier than B0. If it is a giant, it may be slightly earlier, which would

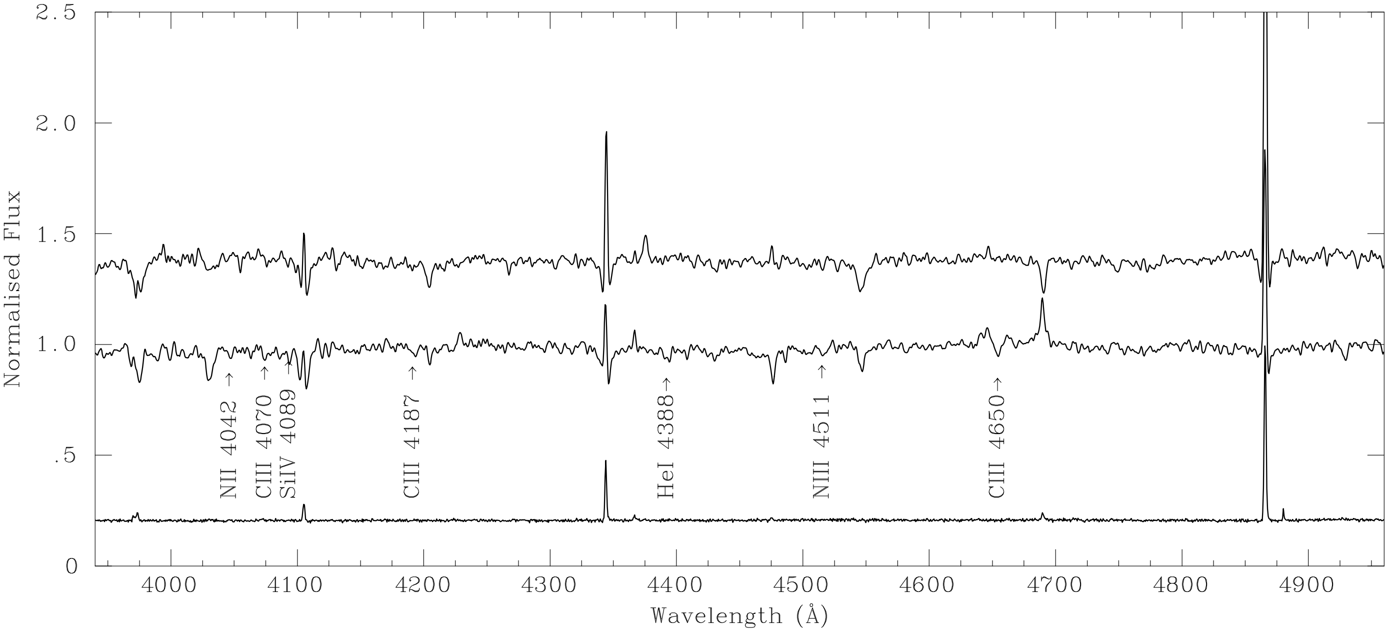

Fig. 3. Blue spectrum of the optical counterpart to LMC X-1 (middle). The top spectrum is that of a second O-type star lying on the slit. The scale is set so that the photospheric features are clearly visible. The bottom spectrum is a sky spectrum taken very close to the position of LMC X-1, showing the very bright emission lines produced in the nebula surrounding the star (arbitrarily scaled). See Fig. 2 for standards of similar spectral type.

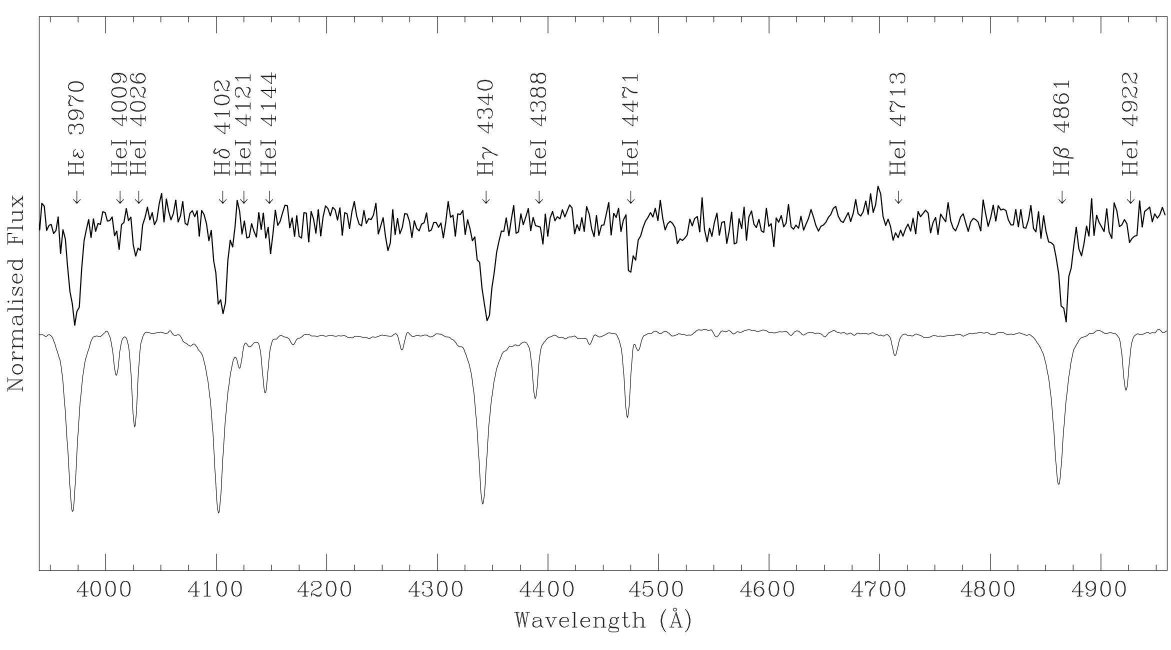

Fig. 4. Blue spectrum of the optical counterpart to LMC X-3 (top). The bottom spectrum is that of the Galactic MK B2V standard 22 Sco. Note the weakness of the Balmer lines in the spectrum of LMC X-3, suggesting that there is a significant contribution to the continuum from another source (the accretion disk).

be supported by the lack of Si III features. Therefore the spectral type is constrained to be B0V or O9.5-B0III

For these spectral types, $(B-V)_0 \approx -0.26$ (Wegner 1994). The source was repeatedly observed by Schmidtke et al. (1996), who found very significant variability by over 0.4 mag. The changes in V were well correlated with changes in the $(B-V)$ colour, as is typical in Be stars. The fainter points measured (in February 1992) were $V \approx 14.28$ and $(B-V) = -0.10$, which are very close to our measurements in October 1996. Assuming that the interstellar reddening is $E(B-V) = 0.10$, the derived intrinsic magnitude is $M_V = -4.2$, typical of a B0V star. If all the reddening is interstellar, $M_V = -4.5$, also compatible with the spectral type.

3.6. CAL 9

This *Einstein* and *ROSAT* variable source was identified with a Be star by Schmidtke et al. (1994). Later Schmidtke et al. (1996) identified this star with HV 2289, a known variable with a large amplitude of variability. Photometry by Schmidtke et al. (1996) showed little variability over more than one year in 1991 − 1993. The faintest points corresponded to $V = 14.5$, $(B - V) = -0.10$.

We have two spectra of this source, one from November 1999 and a second one from October 2000. The emission components of the Balmer and He I lines increased considerably during the interval between the two spectra. Hδ, which was basically in absorption in 1999 shows substantial in-filling in 2000. Our photometric data, taken in late 1996, show the star slightly brighter (though rather redder) than at minimum. All this suggests that the star was in a low state from 1995 to 1999, with the circumstellar disk almost absent and has only recently come back to a Be phase.

The spectrum displayed in Fig. 5 is a sum of our two spectra binned to the same resolution. Again we observe weak He II lines indicating a spectral type close to B0. The absence of He II λ4200Å indicates that it is not an O-type star. Again the condition He II λ4686Å $\simeq$ C IV λ4650Å supports a spectral type B0-B0.2. Assuming that the faintest points in the photometry of Schmidtke et al. (1996) represent values close to those intrinsic to the star, we find $E(B - V) = 0.16$ and hence $M_V = -4.2$. If the interstellar reddening is lower $E(B - V) = 0.08$, $M_V = -4.0$. This values are typical of a B0V star.

3.7. RX J0520.5−6932

This X-ray source has only been seen once at a low X-ray luminosity (Schmidtke et al. 1994). The lightcurve of the optical counterpart, however, exhibits significant modulation with a period of 24.5 d, which is interpreted as the orbital period ((Coe et al. 2001)). The high-resolution spectrum of this source from November 1999 was presented in Coe et al. (2001), where an approximate O9V spectral type was derived. Since the SNR of the spectrum was relatively low, we took two further spectra using the lower-resolution grating #33 in September 2000 and October 2000. When the three spectra are compared, obvious variability in the emission components is seen, with the photospheric component of the Balmer lines becoming progressively deeper as emission disappears. This suggests that the circumstellar envelope is in the process of dispersing.

Figure 6 shows the sum of the three spectra, binned to the same resolution. The strengths of He II $\lambda\lambda$4200,4541Å and the weakness of the Si III lines confirm a spectral type close to O9. This is also in agreement with the relative strengths of the Si IV lines (now visible on the wings of Hδ) and nearby He I lines – if the latter are not affected by emission. At this spectral type, He II λ4686Å is expected to be stronger than C III λ4650Å for the main sequence. The weakness of the He II line suggests a higher luminosity. From the photometric data in Coe et al. (2001), with the derived $E(B - V) \approx 0.3$, the intrinsic magnitude is $M_V = -4.7$. However, the average OGLE photometric values in Coe et al. (2001) imply $E(B - V) = 0.22$. Since there is certainly some circumstellar contribution to this average V (because the source is periodically variable), the derived $M_V = -4.5$ has to be taken as an upper limit. Therefore the photometric data support a main-sequence classification. We adopt O9V.

3.8. RX J0544.1−7100

This source, identified with 1SAX J0544.1−710, is a transient X-ray pulsar ($P_{\rm s} = 96$ s) with the hardest X-ray spectrum observed by *ROSAT* in the LMC (Haberl & Pietsch 1999). As in the case of RX J0520.5−6932, observations of the optical counterpart were presented by Coe et al. (2001), who found it to display large variability in the I-band lightcurve and Hα in emission. An approximate spectral type of B0V was proposed, based on the spectrum obtained for this campaign in November 1999. Again, we have taken a second lower-resolution spectrum of this source in October 2000.

Figure 6 shows the sum of the two spectra, binned to the same resolution. The strengths of He II $\lambda\lambda$4541, 4686Å are compatible with a B0V spectral type, but C III λ4650Å is far too weak, even for an LMC source. This could be related to the presence of the strong line at $\sim$ 4045Å (real, since it is present in both spectra), which would then be a N II blend, suggesting some N enhancement. Some peculiarity, however, remains, since the features at λ4210Å and λ4829Å which we cannot identify, also seem to be real. Higher resolution observations of this object are necessary

This star is photometrically very variable. The OGLE I-band lightcurve (Coe et al. 2001) shows variations of ~ 0.3 mag. The photometry from January 1999 indicates $(B - V) = 0.1$ implying $E(B - V) = 0.36$. Such value is rather high to be purely interstellar and again indicates some contribution from the circumstellar disk. Taking the interstellar contribution to be within $E_{\rm is} = 0.10$ and $E_{\rm is} = 0.30$, we obtain M_V in the range −3.3 to −3.9, which correspond to a dwarf in the B0 − B1 range.

3.9. RX J0529.8−6556

The transient X-ray source RX J0529.8-6556 was detected during one single outburst as a 69.5-s X-ray pulsar by Haberl et al. (1997), who identified it with a relatively bright blue star showing weak Hα emission.

The spectrum of the optical counterpart is displayed in Fig. 7. There is little emission in the Balmer lines, but He I λ4713Å is hardly seen. He II λ4686Å is very weak suggesting a spectral type later than B0. The ratios of the He I lines are compatible with a spectral type close to B0.5. The presence of Si IV λ4089Å is incompatible with a later type. All the metallic lines are very weak and the

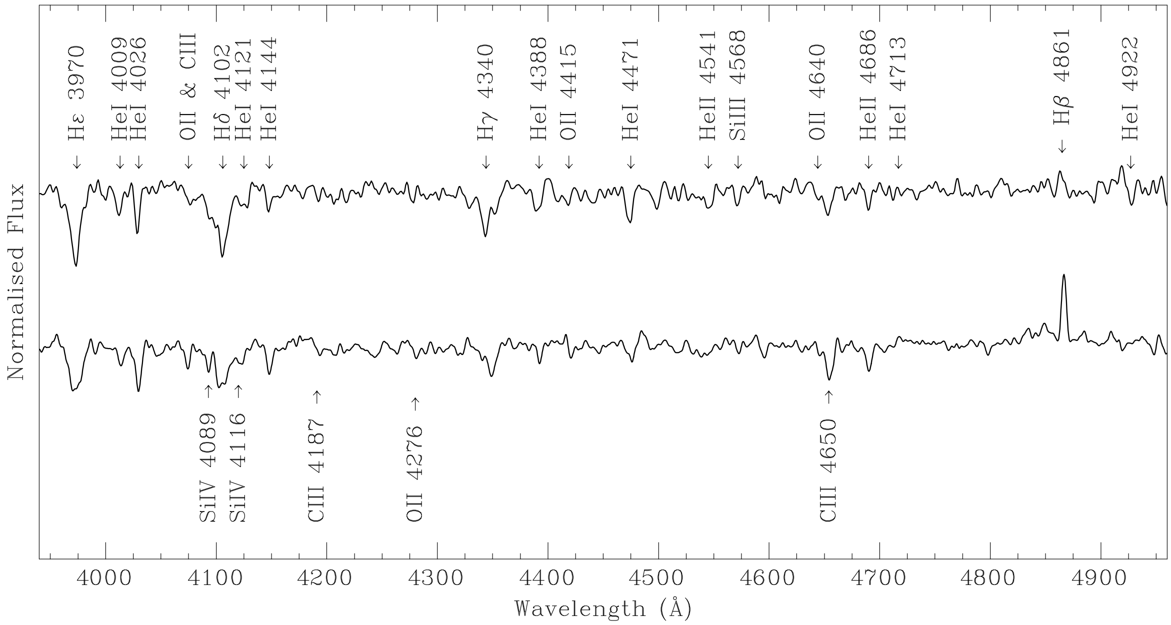

Fig. 5. Blue spectra of the optical counterparts to CAL E (bottom) and CAL 9 (top). The spectra have been smoothed with a $\sigma = 1.4$ Gaussian for display. The absorption feature at $\sim \lambda4510$ Å in the spectrum of CAL 9 appears only in one of the summed spectra and is likely an artifact.

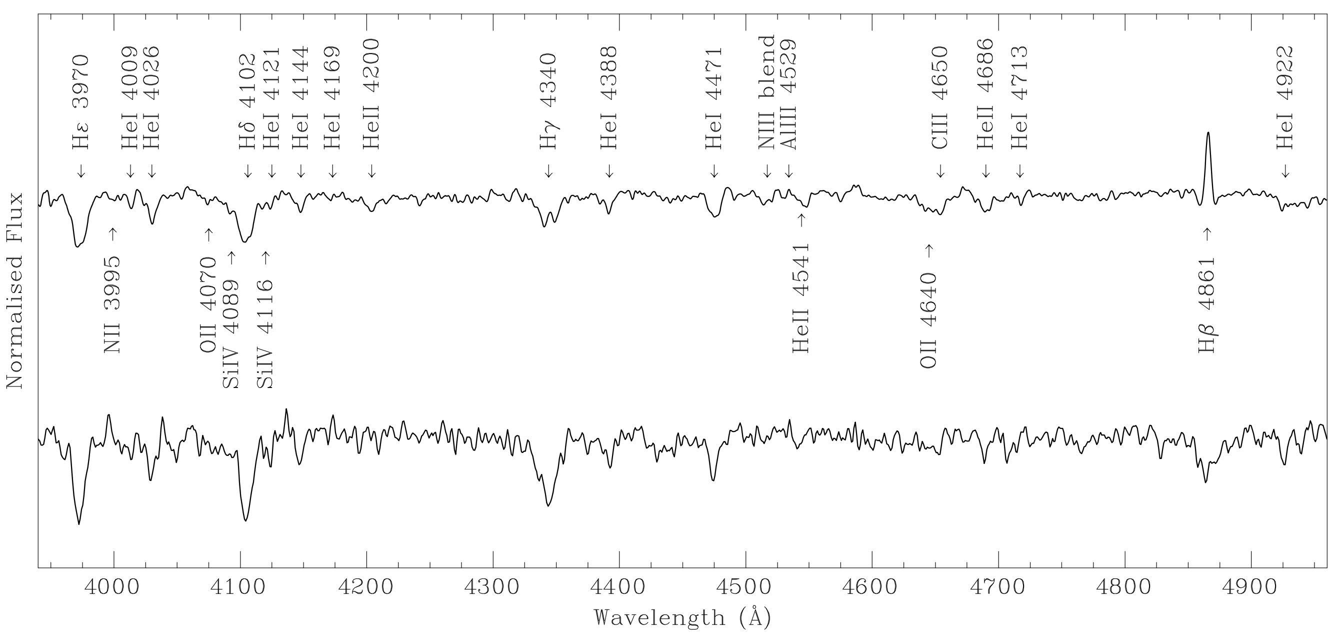

Fig. 6. Summed spectra of the optical counterparts to RX J0520.5−6932 (top) and RX J0544.1−7100 (bottom).

Bowen blend is hardly seen. The spectral type is B0.2 or B0.5, with the weakness of the metallic lines making a main sequence classification much more likely.

Our photometry indicates $(B-V) = -0.16$. The $E(B-V) = 0.08$ is consistent solely with interstellar absorption, which is expected, given the absence of emission in the Balmer lines. The derived $M_V = -3.7$ is consistent with a B0.5V star.

3.10. EXO 0531.1−6609

This X-ray source was discovered by *EXOSAT* during an outburst in October - November 1983 (Pakull et al. 1985). Later it was detected by the X-ray telescope on Spacelab 2 in July/August 1985 at a flux $\sim 10^{37}$ erg s^{-1} (Hanson et al. 1989). Monitoring with *ROSAT* confirmed it to be highly variable. The source was detected at a low level in November 1991 and then during a bright outburst in April 1993 (Haberl et al. 1995b). During the out-

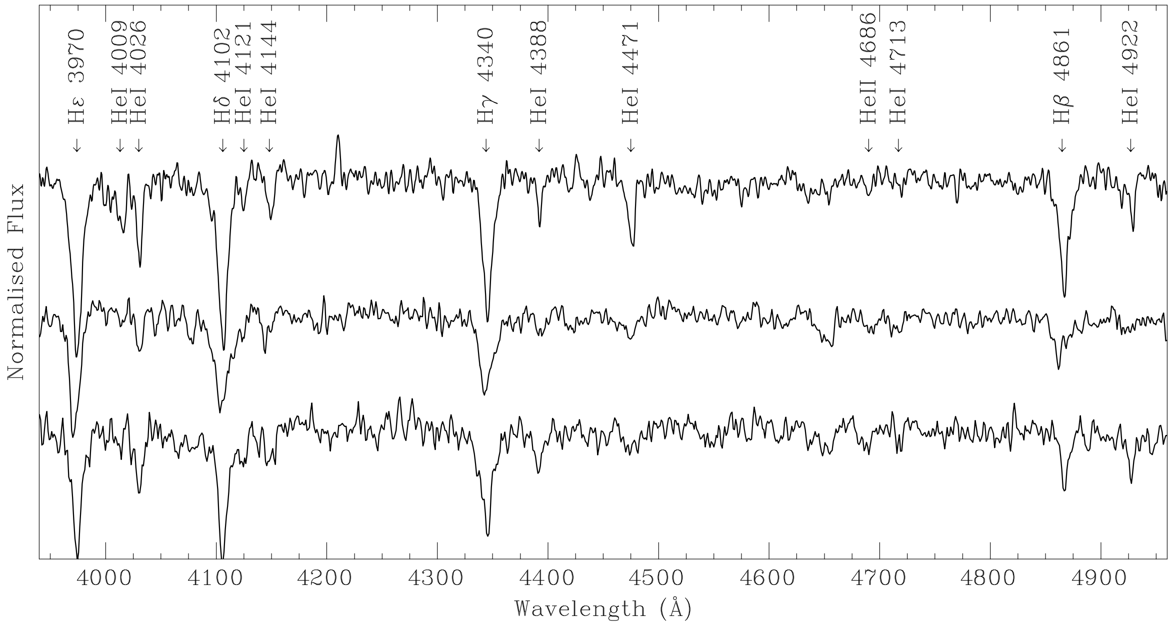

Fig. 7. Blue spectra of the optical counterparts to RX J0529.8−6556 (top), EXO 0531.1−6609 (middle) and H0544−665 (bottom).

burst, pulsations were detected at $P_{\rm s} = 13.7$ s. From a study of the variability of the pulsations, Dennerl et al. (1996) derive a likely (though not certain) orbital solution with $P_{\rm orb} = 24.5$ d and low eccentricity. All the outbursts detected from EXO 0531.1−6609 have been rather longer than the proposed orbital period, suggesting that they are giant outbursts (see Negueruela 1998).

The counterpart is a relatively faint Be star, the Northern component of a very close double. The second star is slightly fainter, but we have not managed to disentangle their contributions in any of our images and cannot therefore derive reliable photometry. Given the rather poor seeing during our spectroscopic observations, even though our spectra were taken with the slit set so as to leave out the companion, we expect some contamination. In any case, spectra taken in 1999 and 2000 do not differ significantly, except for some variability in the in-filling of the cores of Balmer lines. The summed spectrum is displayed in Fig. 7. He II λ4686Å may be very weakly present, indicating a spectral type later than B0. The relatively strong C III λ4650 Å line makes it B1 or earlier. Though several weak lines attributable to O II are visible, the Si III triplet is not visible, suggesting main sequence. This is supported by the broad Balmer lines (except Hβ, which is filled in). A spectral type around B0.7V seems likely.

3.11. H0544−665

H0544−665 was discovered as a weak X-ray source by Johnston et al. (1979) using the *HEAO-1* scanning modulation collimator. Its luminosity $\sim 10^{37}\,{\rm erg\,s^{-1}}$ is typical of a Be/X-ray binary in outburst. In the rather large ($r = 1'$) error box, there is only one object bright enough to be an early-type Be star in the LMC. Based on its large optical variability, van der Klis et al. (1983) proposed it as the optical counterpart, though they did not detect any emission in their spectra. Later Stevens et al. (1999) detected Hα and Hβ in emission in February 1998.

Our spectrum of this source, taken in November 1999 is shown in Fig. 7. The spectrum is rather noisy, due to the relative faintness of the source, but weak He II $\lambda\lambda$ 4541, 4686 Å lines are visible, suggesting a spectral type B0V.

van der Klis et al. (1983) obtained extensive photometry of the source and found that there was a correlation between its brightness and the $(B-V)$ colour, as is typical of Be stars. From their data, some variability in B may be deduced, up to 0.2 mag. Their faintest (and therefore bluest) datapoints imply $V \approx 15.5$, $(B-V) \approx -0.20$. This is consistent with the intrinsic colour of a B0V star reddened with the typical $E(B-V) \approx 0.07$ for LMC sources. However these magnitudes imply $M_V = -3.0$, which is too faint for a B0V star and more in line with B1-B.15V. Since the spectrum seems to be that of a B0V star, we must conclude that the star is underluminous for its spectral type ($M_V = -4.2$ after Vacca et al. 1996).

3.12. 1A 0535−66

Probably the best known and least understood Be/X-ray transient, 1A 0535−66 was discovered by the *Ariel 5* satellite in June 1977, during at outburst in which the flux peaked at $\sim 9 \times 10^{38}\,{\rm erg\,s^{-1}}$ (White & Carpenter 1978). When active, 1A 0535−66 displays very bright short X-ray outbursts separated by 16.6 days, which is believed to be the orbital period. The optical counterpart experiences drastic changes in the spectrum, with the appear-

ance of strong P-Cygni-like emission lines, and brightening by more than 2 mag in the V band (Charles et al. 1983). Detection of a 69-ms pulsation in the X-ray signal has been reported only once (Skinner et al. 1982).

Bright X-ray outbursts from 1A 0535−66 have not been seen since 1983 but some lower level activity has always been observed. Monitoring in the optical between 1993 and 1998 has shown recurrent outbursts, when the source brightens by up to ~ 0.6 mag in V, modulated at a period of 16.651 d, which is identified with the period seen in the X-rays (Alcock et al. 2001). In addition, there is a longer-term modulation with period $P = 420.8 \pm 0.8$ d, corresponding to smoother changes with an amplitude of ≈ 0.4 mag. Apparently, the short outbursts only occur during the phase of the 421-d period in which the source is faint (Alcock et al. 2001).

There is very little difference in the photospheric features between the October 1999 and September 2000 spectra, which correspond to approximate phases $\phi = 0.89$ and $\phi = 0.65$ in the 421-d period as defined by Alcock et al. (2001). Some weak emission can be present in the bottom of some He I lines in the 1999 spectrum. For this reason, we display the 2000 spectrum of the optical counterpart in Fig. 8 together with the B1III MK standard HD 23180. The overall appearance of both spectra is very similar. The Si III lines are weaker in the spectrum of 1A 0535−66, as corresponds to an LMC source. However, the O II blend at λ4650Å and Mg II λ4481Å appear stronger than in the Galactic standard, which together with the smaller intensity of H and He I lines would suggest a higher luminosity. In this case, the spectral type of 1A 0535−66 in quiescence would be B1II.

Such a high luminosity would result in a very extended atmosphere, suggesting that 1A 0535−66 may indeed be close to overflowing its Roche lobe at periastron. However, we point out that a weak feature that could be He II λ4686Å is visible in our 2000 spectrum. This feature is not seen in 1999, but He II λ4686Å emission has been observed in 1A 0535−66 even during off states (Hutchings et al. 1985). If some emission was occulting a very weak He II λ4686Å photospheric feature, then the strength of Si IV λ4089Å would support a B0.5 classification. The line at λ4650Å would then be a blend of O II and C III, making the classification B0.5III.

Our spectral classification for 1A 0535−66 as B0.5III is rather different from that of Charles et al. (1983), B2IV, but in good agreement with the estimate from a quiescent spectrum of Pakull & Parmar (1981). The colours of 1A 0535−66 have been observed to change significantly. Pakull & Parmar (1981) report a $(B-V) = -0.20$ during February-April 1980, when the source was in the "off" state. Such value must be the intrinsic colour of the star, since it implies $E(B-V) = 0.04$. The corresponding $V = 14.83$ indicates then $M_V = -3.5$, which may be compatible with a main-sequence star, but certainly not with a giant. Alcock et al. (2001) have suggested that the actual quiescent magnitude of 1A 0535−66 is $V \approx 14.4$ and that the dips at $V \approx 14.8$ are caused by the development of an obscuring shell. Even then $M_V = -4.0$ would be rather lower than expected for a giant star.

3.13. RX J0531.5−6518

This source was detected with the *ROSAT* PSPC in June 1990 (Haberl & Pietsch 1999). The source is probably variable, since other pointings failed to detect it. The error circle shown by Haberl & Pietsch (1999) contains only one relatively bright object. The spectrum of this star taken in November 1999 seems typical of a normal early-type B star. The spectrum from October 2000 shows substantial infilling of Hβ and a decrease in the intensity of all Balmer lines. Therefore this object is probably a Be star coming back from an extended disk-less phase and so the correct optical counterpart.

The summed spectrum of the star is displayed in Fig. 9. No He II lines are visible and the Bowen blend seems to be absent. The absence of any Si III lines, the ratios of the He I lines and the strength of Mg II λ4481Å indicate a spectral type B2. However, the presence of some O II lines is surprising, especially because the line tentatively identified as N II λ3995 Å would be indicating N enhancement. We provisionally adopt a spectral type B2V, though some anomaly seems to be present.

Our photometry gives $(B-V) = -0.16 \pm 0.03$, implying a reddening $E(B-V) = 0.05$, consistent with interstellar. This again favours the idea that the object was not in a Be phase during 1999. The derived $M_V = -2.4$ is consistent with a B2V spectral type (Schmidt-Kaler 1982).

3.14. RX J0535.0−6700

The variable source RX J0535.0−6700 was observed by the *ROSAT* PSPC at a luminosity $\sim 3 \times 10^{35}$ erg s^{-1} (Haberl & Pietsch 1999). Its positional coincidence with an optically variable star in the LMC (RGC28 in Reid et al. 1988) is very good. The star displays periodic variability in its I-band lightcurve at $P = 241$ d, which Reid et al. (1998) originally believed to be the period of a Mira variable. Since the optical counterpart to 0535−66 also appears in this catalogue, mistakenly taken by a Mira variable, Haberl & Pietsch (1999) suggest that RGC28 might be a Be star, in which case it would be the optical counterpart and the variability would be related to the orbital period.

The spectrum of RGC28 is displayed in Fig 9. The object is obviously an early-type Be star, confirming the suspicion of Haberl & Pietsch (1999), and likely the optical counterpart to RX J0535.0−6700. Hβ is almost completely filled in by emission. The presence of He II $\lambda\lambda$4200, 4541Å indicates a spectral type B0 or earlier. If the object was a Galactic source, the ratio C III λ4650Å$\simeq$ He II λ4686Å would indicate a B0V star. In the LMC, however, the relatively strong metallic spectrum could indicate a slightly higher luminosity and therefore slightly earlier spectral

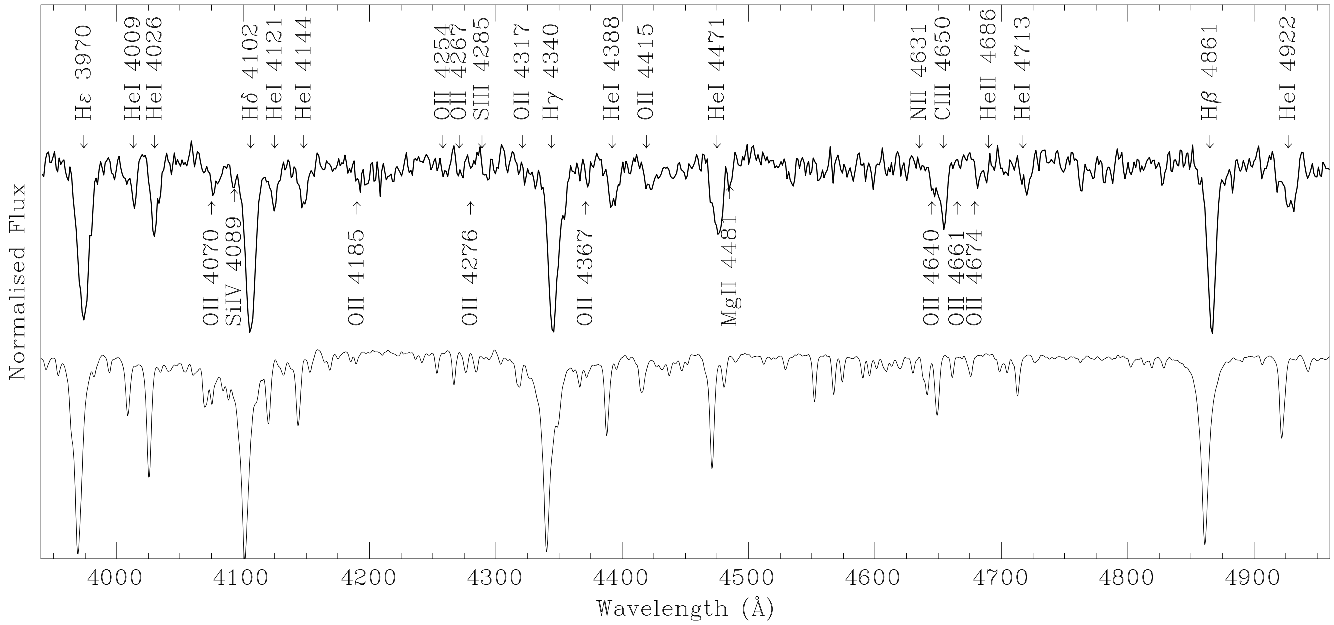

Fig. 8. The spectrum of the optical counterpart to 1A 0535−66 (top) compared to the B1III standard HD 23180.

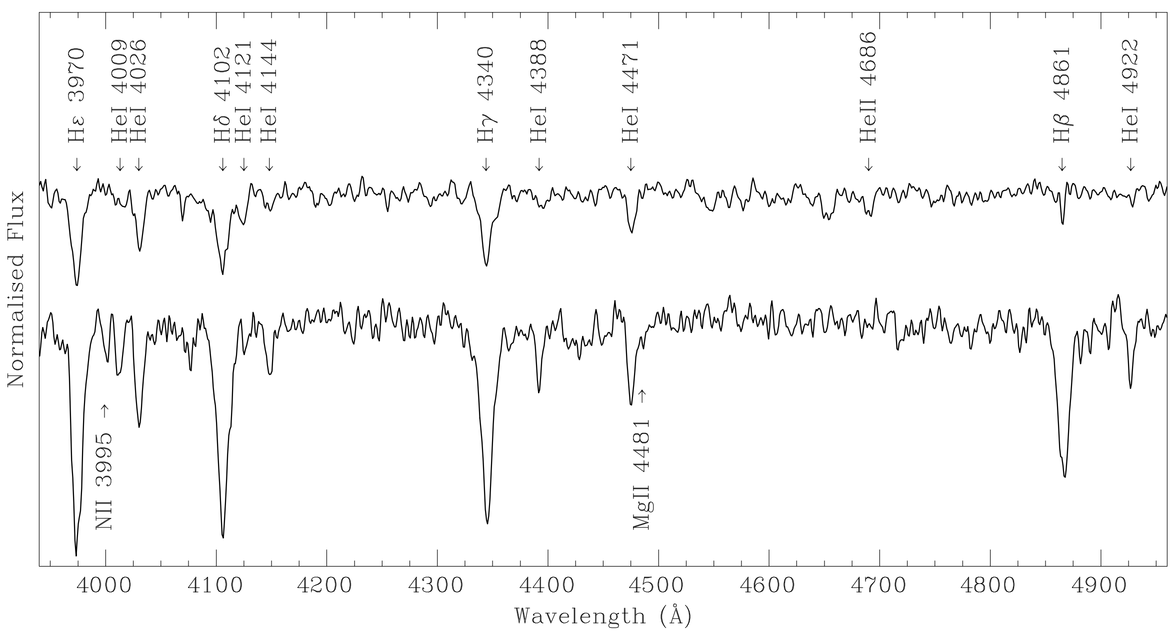

Fig. 9. Blue spectra of the proposed optical counterparts to RX J0531.5−6518 (bottom) and RX J0535.0−6700 (top).

type, making O9.5III in principle also compatible with the observations.

Our photometry indicates $(B-V) = -0.07$. The interstellar reddening is then at most $E(B-V) = -0.19$. This implies $M_V = -4.0$, indicating the main sequence classification. Therefore we adopt B0V.

4. Discussion

We have obtained accurate spectral classifications for an almost complete sample of HMXBs in the LMC. Among these objects, there are three well-known bright persistent X-ray sources, two of which are considered to be black hole candidates (LMC X-1, O8III-V; LMC X-3, B2?Vp), while the third is a bright X-ray pulsar fed by Roche-Lobe overflow from the O8III companion (LMC X-4). In addition, we have found that the optical counterpart to RX J0532.5−6551 has a spectral type B0II and therefore this source is likely to be a wind-fed accreting system, like Vela X-1. All the other sources in the sample are likely Be/X-ray binaries. Eight of them had been considered as such in previous work (of which, 5 are X-ray pulsars) and two further suggestions seem to be confirmed by our results. The list of confirmed and likely Be/X-ray binaries in the

LMC is summarized in Table 2, while the list of possible HMXBs which have not been included in this investigation is given in Table 3.

Since we have relied on the derived absolute magnitudes of our objects to determine their luminosity classes, the choice of a particular calibration has a direct bearing on the results. Throughout Section 3, we have used the calibration of Vacca et al. (1996) for O-type stars, complemented by that of Schmidt-Kaler (1982) for early B stars. By using this calibrations, we have found that three objects seem to be underluminous for their spectral type: LMC X-4 is moderately underluminous for O8V, though a spectral type is difficult to assign. On the other hand, both 1A 0538−66 and H0544−665 have well defined spectral types and their absolute magnitudes seem to be slightly lower than expected.

The distance modulus to the LMC used through this work is $(M-m)_0 = 18.24$, after Udalsky (2000). The validity of this value is still open to discussion, with many authors supporting a value $(M-m)_0 = 18.5$. We just note here that the distance modulus adopted does not affect in any significant way the results obtained. The only changes that would result from adopting the "longer" distance would be that the intrinsic luminosity of the optical companion of LMC X-4 would become marginally compatible with an O8V spectral type (but still not with O8III) and that the intrinsic luminosity of EQ 050246.6−663032.4 (CAL E) would then be compatible with a B0III spectral type. H0544−665 and 1A 0538−66 would still be underluminous for their spectral types.

A new calibration based on Hipparcos distances has been derived by Wegner (2000), who finds on average rather lower absolute magnitudes at a given spectral type than previously assumed (typically by ~ 1 mag). By using this calibration, we could solve the problem of our three underluminous objects, but we would create a larger one, since the magnitudes that we derive (typically $M_V \approx -4$ for B0V objects) would then mean that all the other counterparts are bright giants. Therefore we conclude that our data support the older "brighter" calibrations, even though we have used a "short" distance for the LMC.

4.1. A preliminary comparison to the Galactic population

Our sample of the LMC HMXB population is complete, in the sense that we have observed all the systems with confirmed optical counterparts. As shown in Table 3, only two possible Be/X-ray binaries are left out (RX J0516.0−6916 and RX J0532.4−6535). The main limitation to any conclusions to be drawn from this sample (i.e., how representative it is?) stems from our inability to judge how many other X-ray sources remain undiscovered. In this respect, it is clear that, unlike in the Galaxy, we are not missing any sources because they are very absorbed. The *ROSAT* PSPC pointed at most locations in the LMC more than once, with many fields being observed close to ten times (Haberl & Pietsch 1999). Since the sensitivity limit of *ROSAT* allowed the detection of relatively weak LMC sources, only very weak persistent X-ray sources (with $L_{\rm x} \lesssim 10^{34}\,{\rm erg\,s^{-1}}$) may have been missed, specially in fields where no deep exposures have been carried out.

The main uncertainty is therefore what fraction of transient sources has not been discovered yet because they were not active when they were looked at. There is no obvious way to assess this number, but a comparison with the Galactic sources may indicate that the census is still relatively incomplete, since a large fraction of Be/X-ray transients are only active as X-ray sources for relatively short periods.

At first sight, the LMC HXMB population is not significantly different from the Galactic one. All the LMC systems seem to have Galactic equivalents. LMC X-4 is similar to the Roche-Lobe overflow accreting pulsar Cen X-3. LMC X-1 would be its equivalent with a black hole companion, not too different from Cyg X-1, except in the mass transfer mechanism. LMC X-3 is similar to the recently found black hole candidate SAX J1819.3−2525/V4641 Sgr for whose components (B9III+BH) Orosz et al. (2001) derive masses which are quite close to those estimated for LMC X-3. The fact that SAX J1819.3−2525 is a transient X-ray source, while LMC X-3 is persistent, may be related to the smaller orbit of LMC X-3.

Among the list of known and probable HMXBs of Liu et al. (2000) we find that there are 40 Galactic systems with identified optical counterparts – leaving aside some objects like γ Cas, 1E 1024.0−5732 or 1H 0521+373 whose nature as HMXBs is unclear. Of these, 23 are BeXBs and 10 are SXBs. 7 objects are not included in any of the two groups. In particular, we exclude the binaries 1E 0236.6+6100 and SAX J0635+0533 from the count of Be/X-ray binaries, because they are not believed to be accretion driven. We have also excluded XTE J0421+560, because the exact nature of its two components is still unknown. The respective fractions are then 25% SXBs and 58% BeXBs. Adding objects without optical counterparts which are believed to belong to one of the two groups because of their X-ray properties or orbital solutions gives 13 SXBs and 37 BeXBs. The fraction SXBs/BeXBs among systems with identified counterparts is 0.43, which reduces to 0.35 when candidate unidentified sources are added.

Of the 10 Galactic SXBs (and 13 likely SXBs), only one (Cen X-3) is powered by Roche-lobe overflow (RLO). All the others are wind-fed systems. Moreover, three of the Galactic HMXBs that have not been included in any of the two groups are also wind-fed X-ray sources: RX J1826.2−1450 and 4U 2206+54 contain main-sequence O-type stars (c.f. Negueruela & Reig 2001) and Cyg X-3 likely contains a Wolf-Rayet star. This means that we know of 16 wind-fed X-ray sources in the Galaxy (most of them persistent and with $L_{\rm x} \gtrsim 10^{35}\,{\rm erg\,s^{-1}}$) against 1 (or maybe 2 if RX J0541.4−6936 really belongs to this category) such sources in the LMC. Since some wind-fed systems are weaker X-ray sources ($L_{\rm x} \approx 10^{34}\,{\rm erg\,s^{-1}}$), the Galactic sample may not be complete.

A simple mass ratio argument, if the stellar populations of both Galaxies are similar, would predict a ratio of 10-12 (Suntzeff et al. 1992) more X-ray binaries in the Milky Way than in the LMC. Therefore the low number of wind-fed systems in the LMC is not surprising in principle.

What sets out a difference is the fact that for one or two wind-fed supergiants, there are 3 RLO persistent bright sources in the LMC. This is in contrast to the Galaxy, where only one such system (two RLO sources with massive companions, if the transient black hole candidate SAX J1819.3−2525 is counted) is known. Moreover, the three donors in the LMC RLO sources are quite close to the main sequence, while the donor in Cen X-3, as the donor in SMC X-1 – the only similar source in the Small Magellanic Cloud –, is rather more evolved. Since no selection effects are expected to be so strong as to affect the number of persistent sources with $L_{\rm x} \approx 10^{38}\,{\rm erg\,s^{-1}}$ detected in our Galaxy, and a mass ratio argument would predict a much larger number of RLO objects, there is a strong suggestion here of some significant difference. Though the numbers involved are too small to attempt any statistics, there is good reason to suspect that, for some reason, binary evolution is more likely to result in close binaries with black holes in the LMC than in the Milky Way, as has been discussed by several authors (e.g., Johnston et al. 1979; Pakull 1898). This seems to be the only significant difference among the two populations and it is unclear whether it can be assigned to the effects of lower metallicity in binary evolution (e.g., through weaker stellar winds resulting in higher pre-supernova core masses) – see Helfand & Moran (2001) for a more thorough discussion.

Among the objects in our LMC sample, the fraction of BeXBs is 71%. If all the proposed HMXBs in Table 3 are added, the proportion is 70%. The corresponding fraction for the Galactic sample (i.e. BeXB/HMXB) is 58% for systems with optical counterparts and 65% for all systems (i.e., identified + candidates). The fact that the fraction is so similar in both galaxies strongly suggests that the selection effects dominating our knowledge of the HMXB population are similar – i.e., in both cases, the main bias results from the incompleteness of the Be/X-ray binary sample, due to their transient X-ray source condition.

4.2. The spectral distribution of Be/X-ray binaries

The spectral distribution of the optical counterparts to Galactic Be/X-ray binaries was studied by Negueruela (1998), who found it to be very different from the spectral distribution of isolated Be stars. The spectral distribution of optical counterparts peaks sharply at B0 and does not extend beyond B2 (roughly corresponding to $\approx 10\,M_{\odot}$). Such distribution can be explained if one assumes that during the mass transfer phase previous to the formation of the Be/X-ray binary (see next Section) material lost from the system carries away a large amount of angular momentum (Van Bever & Vanbeveren 1997).

Table 2. Be/X-ray binaries in the LMC with their spectral types and other known parameters. See the text for references.

Name	$P_{\rm s}$(s)	Spectral Type	Max $L_{\rm x}$ (erg s^{-1})
CAL 9	–	B0V	7×10^{34}
CAL E	4.1	B0V	4×10^{37}
RX J0520.5−6932	–	O9V	5×10^{34}
RX J0529.8−6556	69.5	B0.5V	2×10^{36}
EXO 0531.1−6609	13.7	B0.7V	1×10^{37}
RX J0531.5−6518	–	B2V	3×10^{35}
RX J0535.0−6700	–	B0V	3×10^{35}
1A 0535−66	0.07	B0.5III	1×10^{39}
1SAX J0544.1−7100	96.1	B0V	2×10^{36}
H0544−665	–	B0V	1×10^{37}

The spectral distribution of optical counterparts to LMC Be/X-ray binaries is displayed in Fig. 10, together with that of Galactic sources. The convention adopted has been that of Steele et al. (1998), i.e., the B0 bin contains objects with spectral types in the range O9.5 to B0.2. In order to allow better comparison, the Galactic sample has been replotted using the same convention. This sample contains the 13 X-ray pulsars listed in Negueruela (1998) and three new pulsars discovered by Motch et al. (1997): RX J0440.9+4431, RX J0812.4−3114 and RX J1037.5−5647.

A detailed statistical comparison is left for future work, after the spectral types of some Galactic objects have been reassessed in view of new high-quality spectra. However, it is clear from Fig. 10 that the two distributions are basically identical. Though such similarity is in principle expected (see Van Bever & Vanbeveren 1997), it is encouraging to see it confirmed, because it must mean that:

- The Galactic sample, in spite of all the possible selection effects (see discussion in Negueruela 1998) is representative of the actual spectral distribution.
- In spite of its small size (which could make us doubt of its statistical significance), the LMC sample represents well the population.

If selection effects are having any impact on the spectral distribution observed, such effects must affect both samples. However, selection effects should be very different in the Galactic plane (where we expect extinction towards the optical companions to be the main source of bias in our knowledge of the spectral distribution – in the sense that earlier spectral types are easier to observe and classify) and the LMC (where the main selection effects are the brightness of the X-ray source and our ability to actually identify the counterpart in crowded fields). Therefore we conclude that the observed spectral distribution is not dominated by selection effects. The only selection effect that could affect both samples would be the existence of a population of objects with very low X-ray luminosities, but such a population should be evident in the Solar neigh-

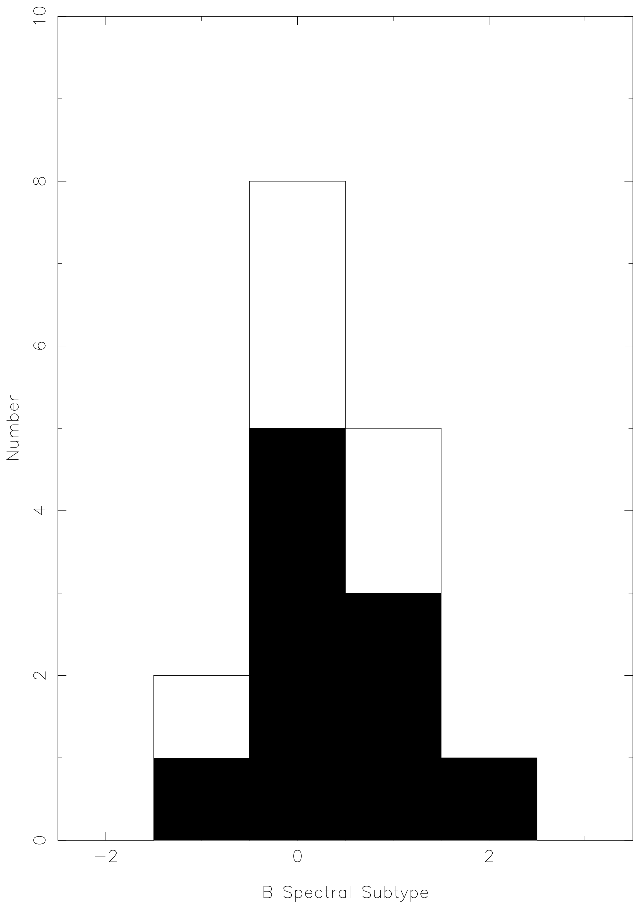

Fig. 10. The spectral distribution of the optical counterparts to Be/X-ray binaries in the LMC (filled) is compared to the distribution of 16 counterparts to Galactic Be/X-ray binaries identified with X-ray pulsars (hollow). Negative spectral subtypes are used to represent O-type stars.

bourhood, if it was a major contributor to the numbers of Be/X-ray binaries.

4.3. Implications for binary evolution

Massive X-ray binaries are born as the result of the evolution of a massive binary in which mass transfer between the two components has taken place before one of them (originally the most massive) became a compact object after gravitational collapse of the core. In what follows we will adopt the following convention: in the massive X-ray binary, we will refer as the *donor* to the massive star which is passing mass to the *compact object* (which will always be referred to as such); in the original binary before the gravitational collapse, we will call the *original primary* to the component which evolved to become the compact object (and which was the more massive component when the system reached the ZAMS) and the *original secondary* to the component that would later become the donor.

Table 3. Other suggested X-ray binaries in the LMC, not included in this sample. References are Cowley et al. (1997) = C97, Haberl & Pietsch (1999) = HP99 and Sasaki et al. (2000) = SHP00.

Name	Suggested Counterpart	Reference
RX J0516.0−6916	B1V	C97
RX J0512.6−6717	–	HP99
RX J0532.4−6535	GRV 0532−6536	HP99
RX J0535.8−6530	–	HP99
RX J0541.4−6936	Sk −69° 271	SHP00
RX J0541.6−6832	BI 267	SHP00

Be/X-ray binaries are generally believed to be formed via a standard evolutionary channel. The progenitor is an intermediate-mass close binary with moderate mass ratio $q \gtrsim 0.5$. The original primary starts transfering mass to its companion after the end of the hydrogen core burning phase (case B), resulting in a helium star and a rejuvenated main sequence star. If the helium star is massive enough, it will undergo a supernova explosion and become a neutron star. If the binary is not disrupted, it can then become a Be/X-ray binary. This model has been developed by Habets (1987), Pols et al. (1991), Portegies Zwart (1995) and Van Bever & Vanbeveren (1997), who have calculated the expected population distribution when different assumptions are made. All these models assume that the original primary must have a mass $\gtrsim 12\,M_{\odot}$ (because otherwise it would not produce a neutron star) and that strong tidal interactions during the mass transfer phase result in the circularization of the orbit. It is implicitly assumed that the Be nature of the original secondary is due to accretion of high-angular-momentum material from the primary, even though no description of the exact physical process has been attempted.

Habets (1987) studied possible evolutionary scenarios and came to the conclusion that, if supernova explosions are always symmetric, only low-eccentricity Be/X-ray binaries may exist, because the exploding helium star has in all cases a much lower mass than its companion and therefore only a small fraction of the system mass is lost in the explosion. As a consequence, van den Heuvel & van Paradijs (1997) conclude that the observational detection of Be/X-ray binaries with very eccentric orbits is proof of the existence of intrinsic kicks imparted to the neutron stars during the collapse that leads to their formation.

A second evolutionary channel has been explored by Habets (1987). In this case, the Be/X-ray binary is formed as the result of the evolution of a binary containing a massive star ($M_{\rm MS} \gtrsim 20\,M_{\odot}$ where $M_{\rm MS}$ is the main sequence mass of the primary) and a rather less massive companion (of mass $M_{*} \sim 10\,M_{\odot}$). Because of the $q \lesssim 0.5$ mass ratio, when the primary fills its Roche lobe, mass transfer is highly non-conservative, a common envelope forms and essentially all of the hydrogen-rich envelope of the primary is lost from the system. The resulting system consists of

a relatively massive He star ($M_{\rm He} \sim 5 - 10\,M_\odot$) and an unaffected secondary. Since the helium star still contains a substantial fraction of the total binary mass, a symmetric supernova explosion can now result in a neutron star orbiting a Be star in a very eccentric orbit, ($e = M_{\rm lost}/M_{\rm left}$, where $M_{\rm lost}$ is the mass lost from the system during the explosion and $M_{\rm left} = M_* + M_{\rm x}$ is the mass of the two components after the explosion).

An important limitation found by Habets (1987) is that, because of the initial conditions required, this channel may only explain Be/X-ray binaries in which a neutron star orbits a low-mass Be star in a close, eccentric orbit. This channel cannot produce systems with either massive donors ($M_* \gtrsim 15\,M_\odot$) or wide orbits. Also important is the fact that, since the original secondary is left basically unaffected by the whole process, it has to be implicitly accepted that it becomes a Be star for some *intrinsic* reason, unlike in the first channel considered.

The spectral distribution found for Be/X-ray binaries in both the Milky Way and the LMC, sharply peaked at spectral type B0 (roughly corresponding to $M_* \approx 16\,M_\odot$) and not extending beyond B2 ($M_* \approx 10\,M_\odot$) strongly argues against the second channel contributing significantly to the formation of Be/X-ray binaries. It is therefore strong indirect evidence in support of the existence of supernova kicks.

In spite of this, the second channel is not only physically possible, but almost certainly realized: a system like LMC X-3 (in which the donor is *not* a Be star) must have formed through such a process, since the original primary must have been sufficiently massive to result in a black hole and the original secondary cannot have been more massive than the present $M_* \lesssim 8\,M_\odot$. Therefore, in the original system, $q \lesssim 0.3$ and non-conservative evolution must have occurred – perhaps through case C mass transfer, as in the models by Brown et al. (2001), since Wellstein & Langer (1999) argue that cases A and B cannot result in black holes.

Though it is not impossible that some of the Be/X-ray binaries with lower-mass donors may have formed through the second channel, it is clear that most must have followed the first channel. Taken at face value, the dearth (or even absence) of Be/X-ray binaries forming through the second channel could be interpreted as a suggestion that a star does not develop Be characteristics due to intrinsic reasons, but must have undergone a process of mass transfer in a binary, as discussed by Gies (2000). Such scenario is in disagreement with the population synthesis models of Portegies Zwart (1995) and van Bever & Vanbeveren (1997), which indicate that not all Be stars may have formed through binary evolution and therefore support an intrinsic cause for the Be phenomenon. The dominance of the first channel may then simply be a reflection of a preference for binary systems which originally have a mass ratio $q \approx 1$. If the progenitor binaries that will evolve through the second channel are much less numerous than those which follow the first, their end products will naturally be also a minority.

It is, however, intriguing to note that, while *no* system containing a Be star and a black hole is known, several systems containing (non-emission) OB stars and a black hole are known, and their donors span a wide range of spectral types. Since their number is still relatively low, one can attribute the absence of Be + black hole binaries to low number statistics. This is, in principle, a valid argument, but it must be noted that black hole binaries with a Be companion should have a much longer lifetime as an X-ray source than any OB + black hole binary, because a mechanism for mass transfer (the Be disk) exists during a longer period. The situation should not be very different from binaries containing a neutron star, where close to 70% of systems known are Be/X-ray binaries. Therefore the absence of known Be + black hole binaries strongly suggests that there is some physical reason why Be + black hole binaries cannot be formed or are not bright X-ray sources.

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